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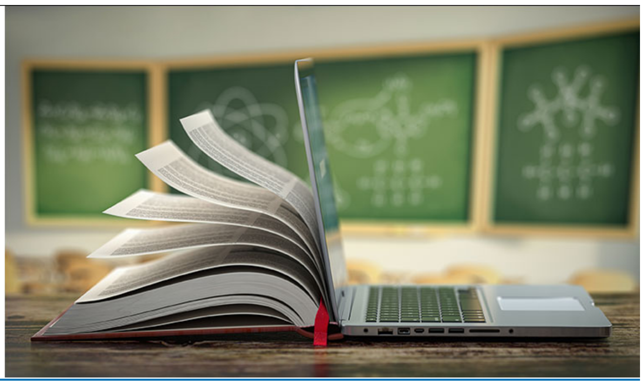

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Evolution of the Safety of Fast Neutron Reactors

N N Oshkanov[1], S E Shcheklein[1]

[1]Ural Federal University, Mira 19, Ekaterinburg 620002, Russia

E-mail: nickolai.oshkanov@yandex.ru

Abstract. In its history, fast neutron reactors (BR) have gone through a long evolutionary period. However in general, BRs have gone the way of the evolutionary development. The function of retention radioactivity in case of an accident was performed by BRs safety vessels. For protection against external influences, new BR projects must be constructed containments. In the function of the reactor core cooling, changes have occurred related to the transition of the emergency cooling from the water circuit to the intermediate sodium circuit. Developments in emergency cooling systems are associated with the placement of an emergency heat exchanger inside the reactor, and the use of natural circulation in sodium and air. In the function on reactivity controlling due to the increase in core sizes, difficulties arise with the suppression of positive reactivity caused by sodium void reactivity effect. Therefore, in BR projects, the use of sodium plenum over the fuel part of the core and / or use of heterogeneous cores are needed. With an increase in the core sizes, the risk of jamming the long shifts of emergency rods increases. Therefore, it is advisable to transfer the safety rods to the hydraulic suspension in a sodium stream.

1. Introduction

Fast reactors (BR) from the first days of their existence, especially in the nuclear power plants (NPP) mode, showed sustainability of operation. Their attractiveness is conditioned by the possibility of making new fuel in excess of the consumed fuel, and a great safety potential {1-3].

Since the start of the first fast neutron reactor, the EBR-I (USA), whose energy was used to generate electrical energy, has so far built 17 NPPs with BRs. At present, there are three NPPs in operation (BN-600, BN-800, CEFR) - the rest have either completed their service life or have not been commissioned after construction. 9 BR projects are under study (Russia, France, India, Korea, Japan, China) [4].

Of course, at such a large interval, the safety of the BRs could not but undergo development [2, 5]. Fortunately, these changes were evolutionary in nature, which shows of the initially fundamental basis that was incorporated in the BR projects, starting with the first reactors:

- extremely low probability of destruction of the reactor core, and a small degree of consequences from such destruction
- no need to take measures outside the plant in any accidents
- minimum amount of radioactive waste with reliable treatment technology.

The undoubted world leader in the field of BRs is Russia, whose real results in the field of power reactors are indisputable (BN-350, BN-600, BN-800; projects of BN-1200, MBIR, BREST), which was emphasized at the IAEA conference in 2017 [1].

The most common is the integrated design (pool-type) BR with the location of the core and all the equipment of the primary circuit in one reactor vessel (Figure 1) [5]. All fundamental decisions are saved. In the main vessel of the reactor 10 all equipment of the primary circuits located. To eliminate possible depressurization of the main vessel, it is installed in the safety vessel 11. Core 8 is installed on the diagrid. Sub-assemblies of fuel pins (SA) are installed by bottom nozzles in the diagrid 9, from which sodium enters SA.

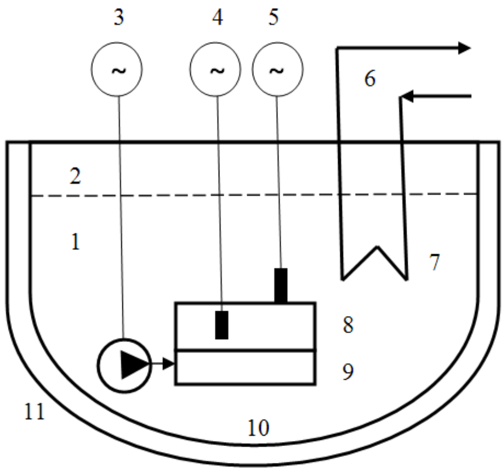

Figure 1. Structure principes of pool-type BR.

1 – sodium, 2 – gas, 3 – pump, 4 – control rod, 5 – shutdown rod, 6 – 2nd circuit, 7 – intermediate heat exchanger, 8 – core, 9 – diagrid, 10 – main vessel, 11 – safety vessel.

The operation of the core is carried out with the help of control rods 4. Emergency protection is carried out using emergency shutdown rods 5. Sodium 1 enters the diagrid with the pump 3. It heated in the core enters the intermediate heat exchanger 7, in which it heats the sodium of the second circuit 6. Sodium has a high boiling point, so it do not need to increase its pressure. To eliminate the entry of air into the reactor during the depressurization of its upper part above sodium, a gas plenum 2 of low pressure is.

The design has undeniable advantages due to factors such as:

- low pressure in the reactor vessel, and a short pipe length of the first circuit (low risk of depressurization);
- the presence of a safety vessel (no risk of loss of coolant);
- large thermal inertia (slow temperature rise in case of accidents);
- simplicity of the decay heat removal
- high boiling point of sodium coolant (no phase transitions during operation).

2. Safety

Consider the evolution of the BR in terms of basic functions:

- retention of radioactivity within the power unit
- the core cooling
- controlling of reactivity.

2.1. Retention of radioactivity within the power unit

This is the most important safety function, which determines the attitude of the whole world to nuclear power. BR has all the barriers to radioactivity established for all types of reactor, in addition they have additional barriers.

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2.1.1. Reactor Barriers.
The first barrier is the fuel matrix. It holds solid radionuclides within a tablet with a high retention rate.

The second barrier is a fuel cladding that retains gaseous radionuclides, as well as solid radionuclides released from the tablet for any reason. The integrity of the fuel claddings is constantly determined by the necessary tools.

The radionuclides emerging from the fuel envelope, as well as sodium-activated radionuclides, are retained by the third barrier, the main reactor body.

The fourth barrier is the safety vessel, in which the main reactor vessel is placed In fact, it is the containment of the reactor, because sodium does not boil up due to its high boiling point and low pressure in reactor when sodium leaves the main body, and, as a result, a large volume of containment is not required.

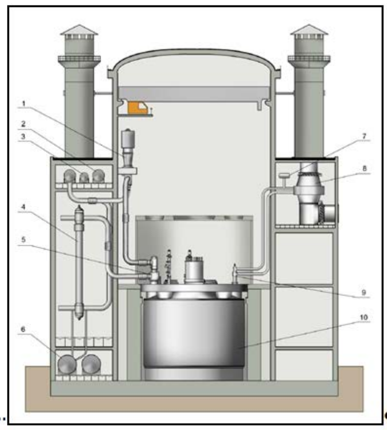
The fifth barrier is the reactor shaft.

The sixth barrier has recently been a core catcher for molten fuel (if that happens).

The seventh barrier is the sodium coolant of the primary circuit. It acts only for the most dangerous of the radionuclides - isotopes of radioactive iodine, which when released in sodium combines with it. The resulting compound has a significantly lower radiation value.

2.1.2. Power unit barriers
The first NPPs with BR were limited to the non-proliferation of radioactivity only by the barriers specified in 2.1.1. It was believed that the safety vessel serves as a containment and no further radioactivity barrier is required. Therefore, the building of the reactor had a general construction purpose and was calculated on general production loads from external influences. We believe that all new BRs should have external containments designed for external influences similarly to other types of modern reactors. For this it is not necessary that they be dense, because during depressurization of BR, there is no pressure increase in the containment due to the absence of a sodium phase transition because the high boiling point of sodium. Recent BRs designs have such containments (Figure 2).

2.2. Core cooling
In normal operation of BR, the heat removal from the core is carried out using a multiloop design. Each loop (Figure 3) consists of a MCP-1 pump for pumping sodium through the core and an intermediate heat exchanger IXH, in which heat is transferred to the secondary coolant and then transferred to the steam generator SG, which produces steam for the turbine



a) SUPERPHENIX (France) [6] b) Design (Russia).

Figure 2. External containment of BRs.

This design does not change its structure, starting with the first BR. It gradually evolved for emergency heat removal - from first using the water circuit (instead of the feed water pump FWP, an emergency water pump is used) before the heat removal into the air using a heat exchanger connected instead of a steam generator [8].

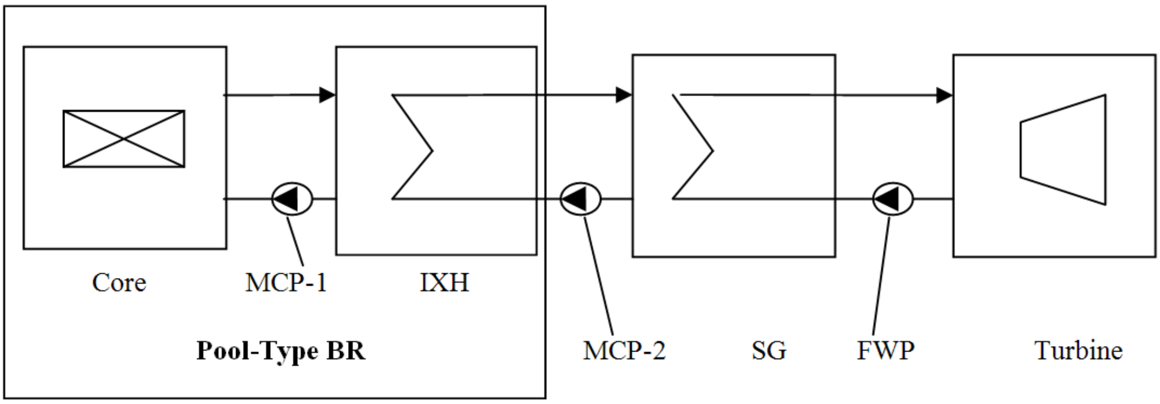


Figure 3. Diagram of a power unit with pool-type BR

However, the fundamental solution is to be applied in new projects related to the placement of emergency heat exchangers in the reactor, and the removal of energy release into the air through natural circulation (Figure 4) [7]. In this variant, there is no need to make switchings under which stress errors or equipment malfunction are possible.

2.3. *Controlling reactivity*

For controlling reactivity, the effects of reactivity and the reactor emergency shutdown system (reactor emergency protection) are important.

2.3.1. *Reactivity effects*

Reactivity as the degree of deviation of a reactor from a critical state is directly related to safety. Perturbations affecting reactivity (reactivity effects) excite various transients. The change in reactivity occurs when the change in temperature of the reactor elements, coolant flow, pressure in the gas plenum, the composition, volume and shape and other parameters of the reactor.

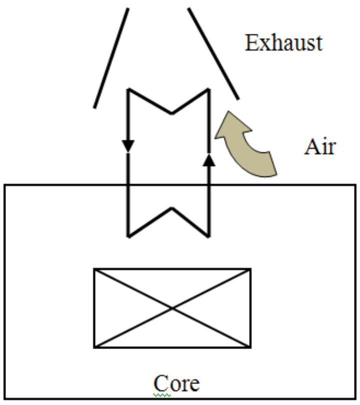


Figure 4. Diagram of the emergency energy removal of the core

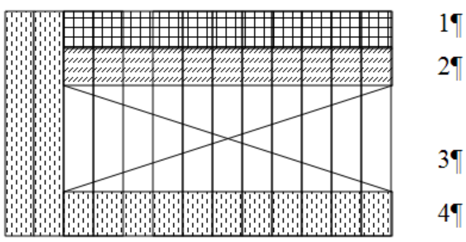


Figure 5. Cut of core with the sodium plenum: *1*– neutron absorber, *2*– sodium, *3* – fuel, *4* – blanket

The temperature effect of reactivity has the greatest effect on reactivity when the temperatures of reactor elements and fuel change. As the temperature of sodium increases, radial expansion of the diagrid, axial expansion of fuel elements, reduction of sodium density, and also the broadening of neutron capture resonance due to the intensification of thermal motion of nuclei (Doppler effect). The expansion of the diagrid, and the axial expansion of the fuel elements increase the volume of the core, causing an increase in neutron leakage from it Due to the Doppler effect, an increasing number of neutrons falls into the expanded resonance region and are captured as the temperature rises. As a result of these phenomena, the reactivity of the reactor decreases.

It should be noted that a decrease in the temperature of the core (for example, with a decrease in power) will cause the opposite effect - release of reactivity. For normal operation, this is compensated by entering the control rods.

Also, the release of positive reactivity occurs with the compaction of the core due to the convergence of SA under external influence (earthquake, shock phenomena, etc.) or the curvature of SA. This phenomenon was observed at the EBR-I reactor [9]. To eliminate this effect, they began to use spacing fins on SA, and subsequent SAs were equipped with contact pads that prevented their convergence [10].

If the above reactivity effects are negative, i.e. as the temperature increases, the reactor power decreases due to the decrease in the density of sodium is not so certain and in some circumstances may cause an increase in power (**the sodium void reactivity effect** (SVER). With a decrease in the density of sodium, sodium boils with the formation of vapor bubbles. This leads to the following parallel processes :

- increase in reactivity due to the growth of fissions due to a hardening of the neutron spectrum and reduction of the nuclei capture on sodium;
- reduced reactivity due to increased neutron leakage because to reduced the nuclei scattering on sodiumi.

These processes compete with each other, and depend on the region of the core. In the center of the core, the effect of hardening of the spectrum prevails over the effect of neutron leakage, which causes an increase in reactivity. At the periphery, neutron leakage prevails, which leads to a decrease in reactivity. These effects also depend on the design of the fuel rods and core. If for small cores, the SVER in the whole core is negative, then for large cores in the whole core, the SVER becomes positive, which creates a safety problem, and can lead to an instantaneous increase in reactor power.

To exclude inserting of positive reactivity - the "Damokl's Sword" of large nuclear power enginering – it is necessary to apply known technical measures, such as minimizing the sodium volume in the core, flattening it to increase neutron leakage, inserting a sodium plenum over the core to increase axial leakage, the heterogeneous core [11].

One of these solutions is shown in Figure 5 – a change in the design of a fuel element by introducing a sodium plenum, and a neutron absorber above it into the upper part of the fuel element.

2.3.2. Emergency shutdown rods

For emergency shutdown of the reactor, special emergency protection rods (AZ) are provided. The AZ rod is controlled by a sahift, the upper end of which is located outside the reactor, and a AZ rod is attached to its lower end (Figure 6). In normal operation, the shift is held in the upper position by electromagnets that are outside the reactor, while the AZ rod is located above the core. When an alarm is received, the electromagnets de-energize, initiating the movement of the AZ rod in the core forcibly or under its own weight. With the growth of reactor size and, as a result, there is a risk of jamming the shift in a narrow channel in which it moves. Despite the small amount of risk it was considered expedient to implement a hydraulic suspension of some AZ rods (the "float" principle) at the sodium flow (Figure 7). In normal operation, these rods are located above the core due to sodium flow. By reducing the sodium flow below the set level, the rods due to their hydraulic weight are inserted into the core, thereby terminating the chain fission reaction in the core.

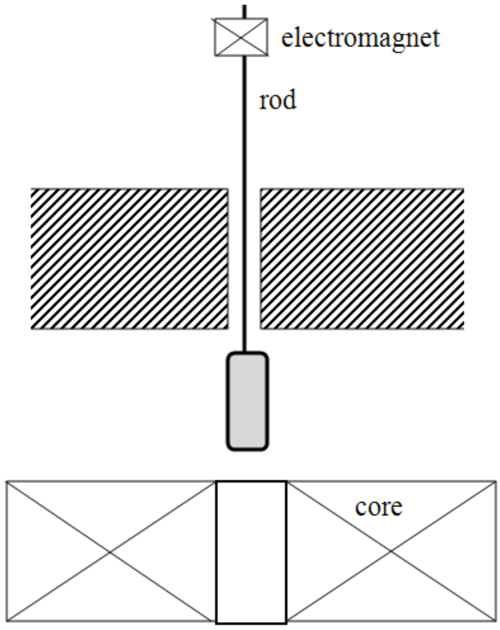


Figure 6. Emergency shutdown rod

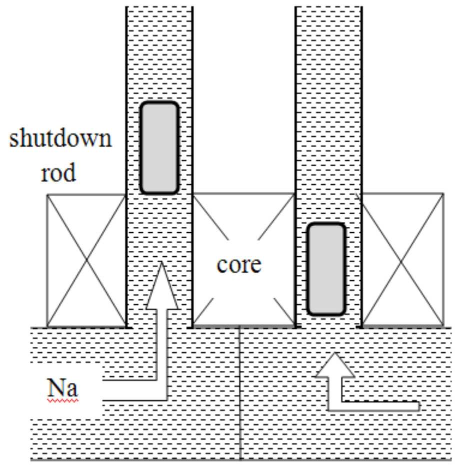


Figure 7. Hydraulic suspension of rod AZ

3. Discussion

We studied the evolution of the BR safety in terms of the basic functions: We note that the basic principles of the design have not changed during the more than 65-year history of BRs. Changes that occurred in the design of equipment were often innovative and increased the quality of DRs, but in general BRs have gone the way of the evolutionary development.

In the radioactivity retention function within the power unit of the first BRs, the reactor buildings did not have containments, which was explained by the sufficiency of the safety vessel. However, in connection with the development of nuclear power, protection against external influences has become increasingly important, therefore, it is necessary to have external containment in new BRs projects.

In the cooling function of the reactor core, evolutionary changes have occurred related to the transition of the reactor emergency cooling down from the water circuit to the intermediate sodium circuit, including using air as a final heat absorber. Recent developments in emergency cooling systems are associated with the placement of an emergency heat exchanger inside the reactor, and the use of natural circulation in the emergency circuit and in the air heat removal path.

In the function on reactivity controlling due to the increase in reactor size, difficulties arise with the suppression of positive reactivity caused by SVER. Therefore, in new BR projects, the use of sodium plenum over the fuel part of the core and use of heterogeneous cores or a combination of these solutions will be required.

4. Conclusions

In their history the BRs have gone through a long evolutionary period. In terms of equipment, of course, there were innovative changes, but in general the reactor did not change the structure laid down in the first reactors.

When developing new projects, it is necessary draw special attention to the use of external containment, the use of an emergency cooling system on the principle of complete natural circulation, and special attention should be drowed to the development of technical measures to achieve a negative sodium void effect.

Acknowledgments
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